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Authors	La Delfa, Santo; NEGUSINI, MONIA; Di Martino, Sabrina; Patanè, Giuseppe
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ORIGINAL PAPER

Geodetic techniques applied to the study of the Etna volcano area (Italy)

Santo La Delfa · Monia Negusini · Sabrina Di Martino · Giuseppe Patanè

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Abstract Volcanic behaviour of Mt. Etna is due to the complex interaction between both the local and the regional stress field involving the eastern Sicily. Eruptions could trigger (be triggered?) during crust extension and/or compression, which are strictly linked with the dynamics of the lower mantle. In this study, very long baseline interferometry (VLBI) space geodesy technique has been used in order to study Etna volcano's activity by means of the crustal deformations between Noto and Matera (located on the African and the Eurasian Plates, respectively). By analysing VLBI data, we obtained the behaviour of the baseline which crosses the Etnean area, from 1990 December to 2003 March, representing the time variations of the distance between the two geodetic stations; the linear trend of the baseline shows a general increasing, pointing out an extension of the crust between them. A detailed analysis of the Noto-Matera baseline allows the identification of three parts of the VLBI curve in the considered period. In the first part of the curve (from 20/12/90 to 09/02/94), VLBI data are rather poor and therefore no reliable consideration about correlation between crust movements and volcanic and seismicity activity has been made. In the second part of the curve (from 09/02/94 to 04/09/00), VLBI data are more frequent and show slightly fluctuations in the distance. Increasing in the extension and compression were observed in the central and in the final part of this period. In the third period (from 04/09/00 to 25/03/03), VLBI data are very sparse even if the time series was quite long; therefore, to fill gaps in the information, we analysed global positioning system (GPS) data. GPS technique performs continuous observations, and we were able to highlight both extensions and compressions in detail. Comparisons between the trend of Noto-Matera baseline length variations, volcanic activity and seismicity in the Etna area show the complexity of the development over time and space of the phenomenology determined by a deep cause which can be traced, in our opinion, to the interaction between the asthenospheric mantle, deep crust and surface crust. Therefore, we state that crustal distension and compression are determined by the lower pulsating mantle.

Keywords Mt. Etna · VLBI · GPS · Mantle · Crust · Earthquakes · Eruptions

Introduction

Mt. Etna is a volcano located in eastern Sicily, in a zone in which the African and Eurasian plates converge (McKenzie 1972; Argus et al. 1989; De Metz et al. 1994). Movements of these two plates, together with the opening of the Tyrrhenian sea which occurred in Tortonian times, have contributed to the arrangement of its current structural and geological framework (Patacca et al. 1990). The subsequent compressive tectonic, occurring since the late Tortonian, probably caused the formation of the Tyrrenian/Appenninic systems. However, the evolution of this convergence area seems to be linked to a fast subduction and roll-back of the Ionian lithosphere beneath the Calabrian Arc spreading in the Tyrrenian Sea (Malinverno and Ryan 1986; Patacca et al. 1990; Faccenna et al. 2001). The

S. La Delfa (✉) · S. Di Martino · G. Patanè
Dipartimento di Scienze Geologiche, Università di Catania,
Corso Italia, 57, 95129 Catania, Italy
e-mail: ladelfa@unict.it

M. Negusini
Istituto di Radioastronomia (IRA), Istituto Nazionale Astrofisica
(INAF), Via Gobetti 101, 40128 Bologna, Italy

development of the instrumental technology and methodology of investigations have allowed to deepen the knowledge of the current geological framework and of the processes linked to the kinematics of the western Mediterranean (Dewey et al. 1989), which is in continuous evolution. These movements, elapsing in time, are also responsible for the seismicity and volcanism of the entire Southern Appennines and Sicily (Behncke 2001). At present, Mt. Etna, together with the Aeolian volcanoes, are the most active volcanic areas of the western Mediterranean. The Maltese-Aeolian faults system, currently considered as the major discontinuities between the African and the Ionian oceanic microplate (Lanzafame and Bousquet 1997), could have contributed to the feeding of the Etnean volcanism through an asthenospheric window (Gvirtzman and Nur 1999). Recent studies show that the present tectonic setting and seismic activity of Mount Etna might result from a local mantle uprise leading to a “horst” (Patanè et al. 2006), probably linked to a deep-rooted hot spot (Montelli et al. 2004), which allows the interpretation of the volcano evolutions (Tanguy et al. 1997; Clocchiatti et al. 1998). In this context, Mt. Etna lies in a region in which compression and extension, together with differential uplift whose intensity decreases from north to south (Ogniben 1966; Di Stefano and Branca 2002; Catalano et al. 2004), rapidly change its local stress field. The changing stress field may cause the onset and the ends of eruptions, as occurred for example in 1984 and 1998 (La Delfa et al. 1999, 2003). Moreover, the uplift, together with the forceful injection of dikes, could provoke the instability of the eastern sector of the volcano found by several authors (Borgia et al. 1992; Froger et al. 2001) and therefore gravitational sliding processes, as occurred for the recent 2001 and 2002–2003 eruptions (Acocella and Neri 2003; Acocella et al. 2003; Branca et al. 2003; Neri et al. 2005). In a recent study, La Delfa et al. (2007) advanced the hypothesis that the gravitative slippage of the eastern flank of Mt. Etna seems to be ascribable to a passive gravitative effect involving the shallower layers of the crust, after mantle uplift. In particular, these authors hypothesized that intrusions of magma and high-temperature aqueous fluids derived from the magma are the cause of changes in the crust rheology from fragile to ductile that, therefore, could favour such shallow gravitative phenomena.

In this study, we describe the observed correlations between recent crustal movements, recorded by the Noto and Matera radio telescopes, the seismicity and the eruptive episodes which occurred at Mt. Etna, in order to find possible links between all these geological processes. The choice of the baseline Noto-Matera is connected to its crossover of the Etnean area (Fig. 1). This region undergoes the convergence between the African and European plates. The main aim of this study is to show that the

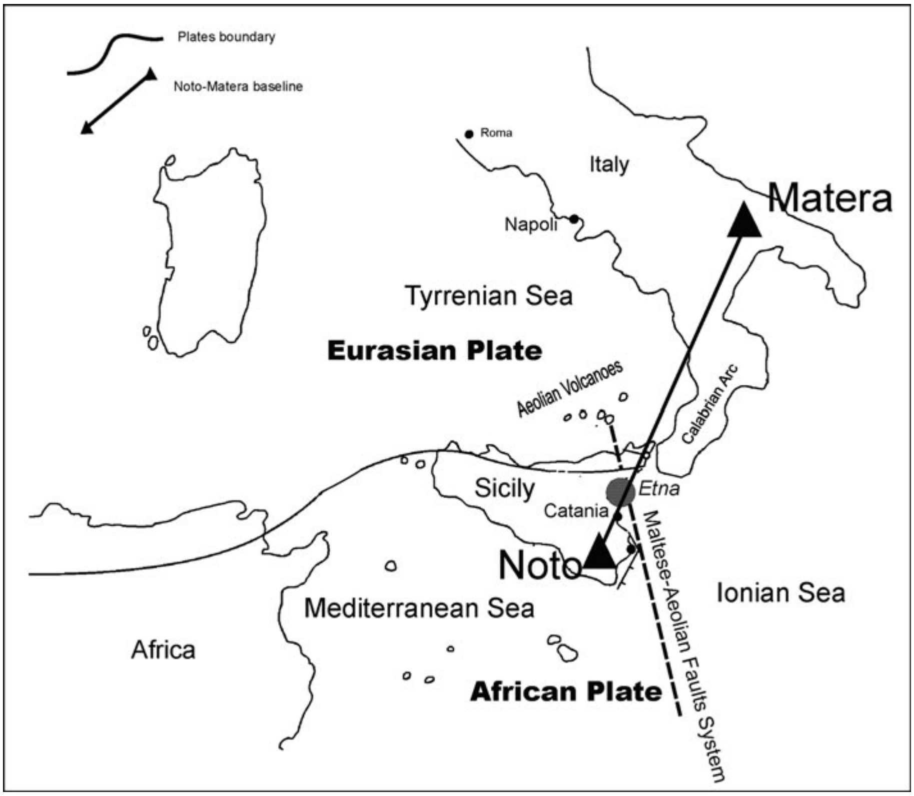

Fig. 1 Sketch map of southern Italy showing Noto and Matera radio telescopes location (*triangle*) and their baseline (*continuous line*)

principal eruptions of Mt. Etna could be triggered mainly when crustal movements, probably due to mantle pulsations, involve this area of the western Mediterranean. In order to achieve this aim, we propose estimated very long baselines interferometry (VLBI) plate motion measurements and review both seismic and volcanic activity occurring on Mt. Etna from 1990 to 2003.

VLBI was developed mainly in North America in the 1960s as an astronomical observation method to determine the inertial reference frame defined by quasars and the earth orientation parameters (EOP). In the 1980s and following decades, VLBI showed its potential to contribute to geophysical research involving surface and internal processes of the Earth, such as tectonic plate motions, ocean and atmosphere loadings, changes in the mass distribution beneath the crust, highlighting its fundamental contribution to reference frames definition.

In particular, the purpose of the geodetic VLBI is to determine accurately the precise positions of the radio telescopes, so relative changes in the antennae locations from time series of measurements indicate tectonic plate motion, regional deformation and local uplift or subsidence. It measures the time differences in the arrival of electromagnetic signals from extragalactic radio sources (delay) at two Earth-based antennae. Repeated determinations of the geometric delay by sequential observation of many radio sources are analysed by standard multi-parameter least squares estimation algorithms to yield high-precision estimates of the VLBI vector baseline (of the order of a few millimetres on baselines up to several thousand kilometers).

A complete review of experiments, models and results of astrometry and geodesy with radio interferometry can be found in Sovers et al. (1998).

VLBI data analysis

The recorded VLBI data are correlated and pre-analysed before to be released to the scientific community as databases, adding models, which includes the effect of precession, nutation, polar motion, UT1, solid Earth tides, ocean loading, pole tide and special and general relativity. Corrections for atmospheric effects are computed using surface meteorological data obtained at each site, and corrections for ionospheric effects are computed from the differences in delay at two frequencies.

VLBI observables have been analysed by means of a multi-parameter weighted least-squares programme, Mark-5 VLBI Analysis Software Calc/Solve package (Petrov 2008), which simultaneously fits all of the data to obtain estimates of geophysical and astrometric parameters.

Data collected at the stations belonging to the VLBI European network (Tomasi et al. 1999; Campbell and Nothnagel 2000), Noto, Matera and Medicina (Italy), Wettzell and Eflsberg (Germany), Nyales20 (Norway), Onsala60 (Sweden), DSS65 (Spain) and others not very often used have been analysed to obtain their position and velocity. All the experiments performed since 1990, when Matera started to record VLBI observations, to 2003, when Matera observations stopped, because of mechanical problems, were selected for this study (Di Martino 2006).

To estimate site motions accurately with VLBI, it is necessary to establish a well-defined terrestrial reference frame. The most used terrestrial reference frames in VLBI data analysis are NNR–Nuvel 1A model (De Metz et al. 1994) and ITRF2005 (Altamimi et al. 2007). There is a more natural way to represent motions by means of a baseline-oriented frame, because VLBI is sensitive to relative positions. For each baseline, it is possible to define a specific reference frame (Ma et al. 1990); components of each baseline are defined relative to a priori estimates of geocentric vectors to the two sites, $\mathbf{X_1}$ and $\mathbf{X_2}$:

$$\mathbf{L} = \mathbf{X_2} - \mathbf{X_1}/|\mathbf{X_2} - \mathbf{X_1}|;\ \mathbf{T} = \mathbf{X_1} \times \mathbf{X_2}/|\mathbf{X_1} \times \mathbf{X_2}|;\ \mathbf{v} = \mathbf{l} \times \mathbf{t}. \tag{1}$$

The length component of each baseline $\mathbf{L}$ is determined by projecting the measured baseline onto $\mathbf{l}$ and corresponds nearly to the magnitude of the measured baseline vector; the transverse component $\mathbf{T}$ is determined by projecting the measured baseline onto $\mathbf{t}$ that is perpendicular to the baseline vector and directed towards the horizon at either site; the vertical component $\mathbf{V}$ is perpendicular to the other two directions, and it is perpendicular at the Earth in the mid point of the baseline. The rates of change of the baseline components are used to estimate relative plate motion.

The VLBI time series 1990–2003 of the baseline length Noto-Matera, which represents the time variation of the distance between the two stations, is shown in Fig. 2; its linear trend shows a general increasing of the length (0.4 ± 0.2 mm/year), thus highlighting an extension of the crust between the two stations. The formal errors of the time series range from 1 to 3 mm, and the rms of the residual series is 3.6 mm. To better understand whether the behaviour can be assessed, other baselines of similar length, but not in volcanic areas, have been analysed, such as Medicina–Wettzell. The rms of the series in the same time period is of the same order (2.6 mm). Also, the other baselines components have been analysed, in particular the vertical one, that should be affected by volcanic activities, but its rms is 3–4 times worst than the horizontal ones and we decided not to use them in this study.

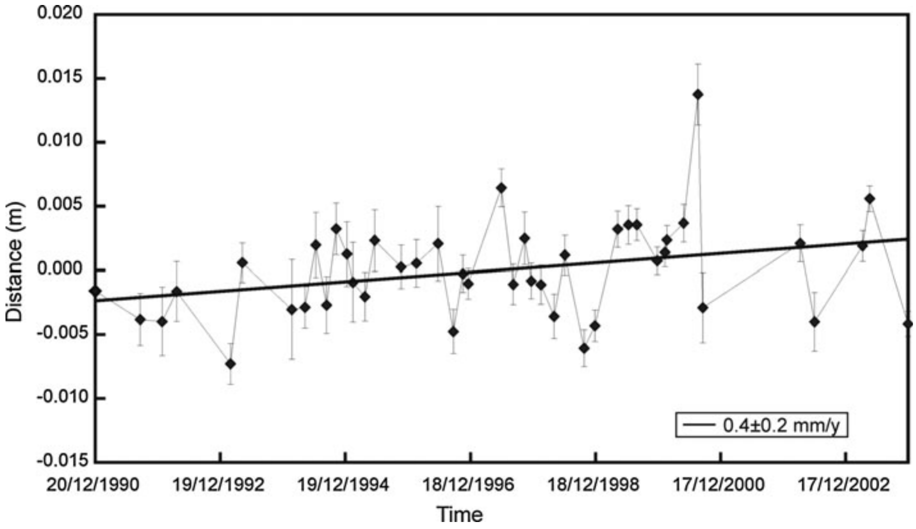

Fig. 2 VLBI baseline Noto-Matera from 1990 December to 2003 January, indicating a general increasing in the length, in the considered period

Summary of volcanic and seismic activity from December 1990 to March 2003

Geodynamics of Mt. Etna in the period between 1990 and 2002 has been described by various researchers, and several models justifying its volcanic behaviour, using seismicity, petrography and geodetic data, have been carried out. In this section, we have made a synthetic/brief but exhaustive summary of both volcanic and seismic activity of Mt. Etna, with the aim of proposing a possible framework of the volcano geodynamics to compare with the crustal deformation recorded through the VLBI observations.

Volcanic activity

After the low-energy seismic and volcanic activity of Mt. Etna in 1990 (Patanè et al. 1991), on 14 December 1991, an eruption from 3,000 m altitude in its SSE flank took place. This volcanic activity, after a phase of slackening which occurred on 29 May 1992, went on till the 31 March 1993. Subsequent to a period of little/weak activity which characterized the following 2 years, brief episodes of lava fountaining resumed at the North-East Crater (NEC) during the second half of 1995 (on 9 and 14 November and on 23 December) and at the beginning of 1996 (La Delfa et al. 2001). From 21 July to 19 August 1996, the volcanic NEC activity evolved into a strong fire fountain (one of each reaching a sustained column 2–3 km high on 25 June (Branca and Del Carlo 2004) and lava flows directed eastwards and southwards (La Delfa et al. 2001). Following (6 November) a resuming in the volcanic activity with weak and sporadic explosions of magmatic material which occurred at the South-East Crater (SEC), at the Bocca Nuova-Central Crater (BNCC) and at the Voragine-Central Crater (VCC). During 1997, a weak effusive activity with small lava flows interested the BNCC and CSE. On 27 March 1998, an eruption with strong Strombolian explosions and lava fountains occurred from the NEC (La Delfa et al. 2003). Strong fire fountains from VCC were observed on 22 July and 5 August. A series of 20 short-lived eruptions occurred at the SEC between September 1998 and January 1999, had preceded the 4 February 1999 eruption, which took place through a fissure on the SSE flank of the same SEC and ended on 5 November 1999. In late 1999 (4 September), fire fountains more than 1,500 m high occurred from the BNCC; meanwhile, short lava flows and weak Strombolian activity interested the SEC. Finally, on 17 October, another eruption with Strombolian activity, fire fountains and overflows westwards took place from the western rim of the BNCC. This last eruption ended on 31 of the same month. The first half of 2000 was characterized by 64 fire fountains from the SEC (from 26 January to 24 June), whereas the second half was characterized by lava emission from SEC (from 26 to 29 August) and a fire fountain on 28 August; intracrateric Strombolian activity on 6, 7 and 16, 17 and 18 September from BNCC volcanic activity, which continued in the following months (from 1 to 13 October and subsequently on 18 and on 21 October. This activity occurred from within the BNCC from 7 to 9 November, on 28 and 30 November. At the same time, there was a lava flow to the SE from 28 to 30 November. Weak Strombolian activity from SEC occurred on 16 and 17 January 2001. From 31 January to the 1 February, a lava out pour started from the north flank of the SEC which carried on till the beginning of the lateral eruption. From the 20 February to 24 March, there was Strombolian activity inside the BN. From 9 May 2001, short lava flows and explosive volcanic activity occurred from SEC till 7 June 2001; subsequently, 24 Strombolian explosions preceded the 17 July 2001 flank eruption. This last eruption interested both the S and the NE flanks of the volcano.

The first one outcrops from a fissure oriented NS at circa 3,100–2,100 m elevation at south base of the SEC and produced lava flow field reaching 1,960 m of elevation (Branca and Del Carlo 2004; Patanè et al. 2004). The NE one occurred from a 2,650 m elevation eruptive fissure. The 2001 eruption ended on 9 August of the same year. Finally, 2002 was characterized by lateral eruptions, which involved both the NE (27 October–4 November) and S (27 October–28 January 2003) flanks of the volcano. These eruptions were accompanied by fire fountains and considerable emissions of lapilli and ash, falling on the S flank of the volcano.

Seismic activity

In 1990, several seismic events with Md ≤ 3.5 prevalently interested most of the summit area, the eastern and the south-eastern sector of the volcano (Patanè et al. 1991). During 1991, Etna was characterized by a relatively high level of microseismicity, occurring mainly on the lower eastern flank of the volcano. From 26 November to 9 December, earthquakes interested the upper northern and western flanks of the volcano. Seismic activity immediately preceding and accompanying the outburst of the 1991 eruption mainly consisted of four swarms, which occurred on 14, 15, 18 and 21–22 December. An important cluster of seismic events (more than 200 shocks) took place on 14 December (Mmax = 3.9) (Patanè et al. 1996). Isolated earthquakes were recorded during 1992 (Vinciguerra et al. 2001), and a low rate of seismicity characterized the period after the end of the 1991–1993 eruption. Weak seismic activity involving the whole volcanic edifice resumed in May 1993, and a minor increase in the seismicity, involving prevalently the upper southern flank of the volcano, occurred from May 1995 (Allard et al. 2006). The following 2 years were characterized by low levels of seismicity till 1997, when an increase in the seismic strain release was observed for the remaining months of the year. In December 1997, the seismic activity decreased; earthquakes were located at middle/high altitude of the volcano. In January 1998, about 500 earthquakes with Md ≤ 3.5 occurred over the whole volcanic area (La Delfa et al. 2003). The seismic activity decreased in February but it increased again in March, before the NEC eruption. In particular, the study of the focal mechanisms of these earthquakes haws shown a variation of the orientation of the pressure and tension axes, which earlier favoured the opening up of eruptive fractures and later retarded the magma from rising and so determined the end of the eruption (La Delfa et al. 2003). Afterwards, the frequency of occurrence of earthquakes showed little variation, but remained constant until the second half of December 1998, when several seismic swarms of earthquakes, of weak magnitude, interested prevalently the higher part of the volcano till the 4 February 1999 SEC eruption. On this day, an earthquake located close to the SEC with magnitude Md = 3.3 took place (La Delfa et al. 2001). The seismic activity remained at low levels until September 2000. On the 5 November, there was a seismic swarm of about 60 quakes with a magnitude generally between 1 and 2 and some with magnitudes of 3.6, 3.1 and 2.6. The 28 November was characterized by a 2.9 magnitude earthquake. Afterwards, an increase in seismicity was recorded during the first half of 2001. In particular, seismic swarms interested the volcano in January and April and in May–June 2001 (Allard et al. 2006). On 17 July 2001, a seismic swarm consisting of more than 2,500 earthquakes interested the southern and the eastern flanks of the volcano. Low levels of seismic activity characterized the second half of 2001. Between the end of 2001 and the beginning of the 2002 eruption, several earthquakes with Md ≥ 1.5 occurred on the eastern flank of Etna (La Delfa et al. 2007). On 26 October, a seismic swarm consisting of more than 300 earthquakes with Md > 1 involved the summit area and the north-east flank of the volcano (Allard et al. 2006). On 29 October, a series of earthquakes with Md ≤ 4.4 occurred on the lower eastern flank of the volcano. Following the seismic swarms which occurred in October, seismic activity remained relatively low during the remaining months of 2002 and during 2003.

In this work, seismicity at Mt. Etna from 1990 to 2003 has been studied considering the strain release obtained from magnitude (M) of earthquakes recorded and analysed by the INGV-Catania section, the University of Catania and the Seismological Observatory of Acireale seismic arrays. The strain-release curve was obtained cumulating $\sqrt{E}$, where E is the energy calculated for each earthquake using the Richter relation (Richter 1958):

$$\log E = 9.9 + 1.9M - 0.024M^2. \tag{2}$$

The obtained strain release curve (Fig. 3) allows comparisons to be made between changes in the seismicity with large-scale crustal movements obtained by VLBI, as described in the following sections.

Data analysis and considerations

In this section, we made an analysis of the variations in baseline length and some correlations with results deriving from geochemical to geophysical data applied in studying volcano geodynamic. A detailed analysis of the Noto-Matera baseline allows us to distinguish three parts of the VLBI curve between 01/01/1991 and 04/05/2003 (Fig. 3). In the first and in the last part (Fig. 3I, III), the VLBI

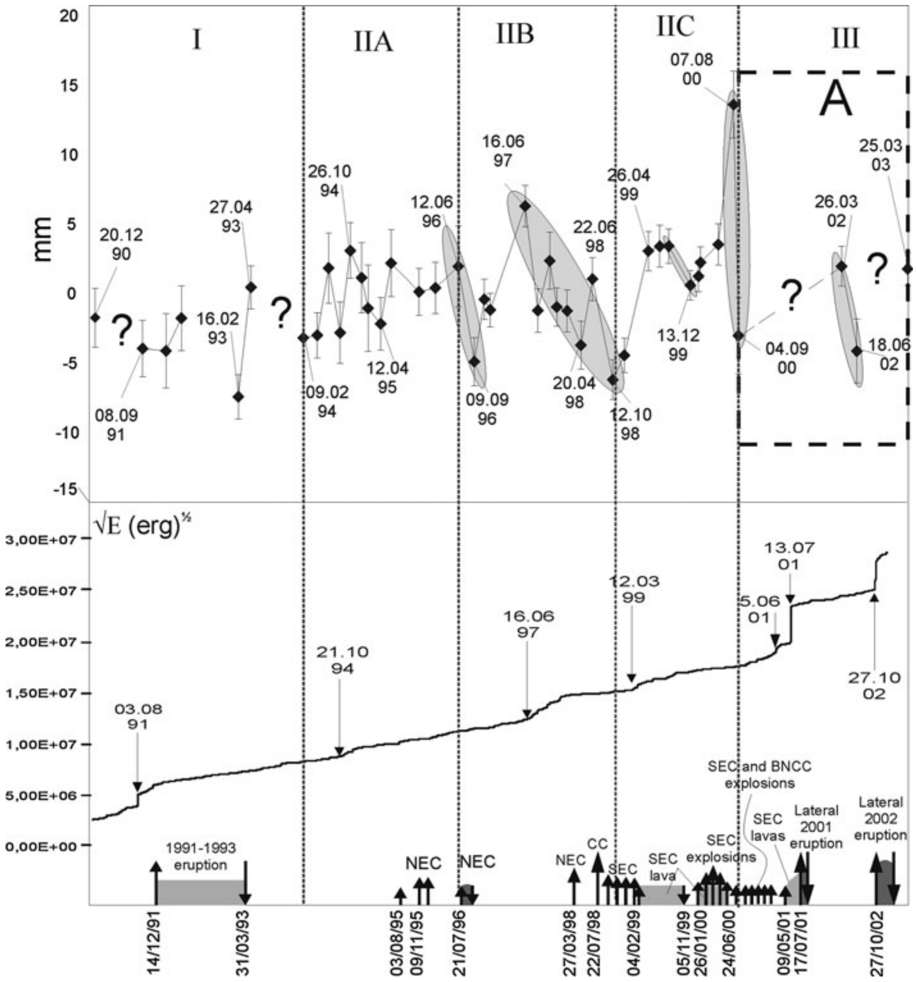

Fig. 3 Comparison between Noto-Matera baseline length and seismic (*strain-release curve*) and eruptive (*arrows*) activity. *Inset* A is detailed reported on Fig. 4 (**b**)

measurements are rather poor, and therefore, only some hypotheses about the meaning of their distance variations as regards the volcano's dynamism will be advanced. In the second part (Fig. 3II), measurements are more frequent and show, between February 1994 and June 1996 (Fig. 3IIA), slight fluctuations of the Noto-Matera distance, inside the bar errors. Subsequently, there is a marked decrease in the distance, and from the first decade of September 1996 till the second half of June 1997, the VLBI curve shows a substantial increasing in its length, reaching a relative maximum on 16 June 1997 (Fig. 3IIB). From the second half of 1997 till the 20 April 1998, the baseline shows an inversion of its dynamic, as it decreases in length. This decrease restarts between the 22 June and the 12 October 1998, after 2 months of interruption. In the second decade of October, a noteworthy increase in the Noto-Matera distance occurred (Fig. 3IIC), showing one absolute maximum on 7 August 2000. Between the first decade of August and the 1 of September, the baseline shows a strong inversion in its dynamic and the decrease in the distance Noto-Matera shows the highest value of the entire period under consideration.

The comparison between the volcanic activity and the temporal trend of the relative VLBI values seems to show that the most numerous and violent explosive and effusive eruptions from the summit craters (NEC, SEC and VC), occurred between 1998 and 2000; furthermore, they took place after and during three noteworthy distensions, as evidenced by increases in the Noto-Matera distance (Fig. 3IIB) from September 1996 to June 1997, from October 1998 to April 1999 and from December 1999 to August 2000. The largest increase in the baseline length occurred between December 1999 and August 2000, which was followed by a similarly sharp decrease in little less than a month (Fig. 3IIC). These significant variations in the Noto-Matera distance seem to be associated with rise of a conspicuous amount of magma, which fed the various lava mountain episodes, effusive activity at the SEC and Strombolian activity at the BNCC until 30 November 2000. After a brief pause that lasted little more than a month, until 16 January 2001, eruptive activity started again mainly in the form of lava flows at the SEC and lasted until the beginning of the lateral eruption in July 2001.

The few and weak eruptive Strombolian-like and/or effusive manifestations which occurred at the summit craters in 1995 and 1996 were rather preceded by quite insignificant fluctuations in the VLBI measurements (Fig. 3IIA). It is not possible to draw any conclusions about the dynamics of the baseline before the 1991–1993 eruption as there are only two measurements over a wide space of time (Fig. 3I). Between April 1993 and February 1994, after the eruption had ended, there is a distinct shortening of the baseline (Fig. 3I, II), which corresponds to a deflation of the volcanic edifice (Massonnet et al. 1995; Bonaccorso et al. 2004). At the same time, the magmatic column within the central conduits dropped by at least 500 m (Rymer et al. 1995). After the 4 December 2000, there are not enough VLBI measurements to define trends (Fig. 3III), so the GPS measurements for Noto and Matera were used (Di Martino 2006). A regional network of 18 GPS stations including Italian and European sites (Aquila, Cagliari, Cosenza, Grasse, Graz-Lustbuehel, Elba, Lampedusa, Maratea, Matera, Medicina, Noto, Trapani-Milo, Reggio Calabria, Tito, Perugia, Wettzell, Vallo della Lucania, Zimmerwald) has been analysed by means of the Bernese software V5.0, following a standard double difference approach. We processed the data from 1996 to 2003 to obtain the time series of daily coordinate solutions of the all stations. Taking into account offsets, changes in the instrumentations, change of the change between Noto and Not1 stations, we obtained the baseline Noto-Matera whose linear trend shows an increasing of the baseline's length of 0.67 ± 0.01 mm/year, which confirms the extension of the crust between the two stations (see Fig. 4a). Though the

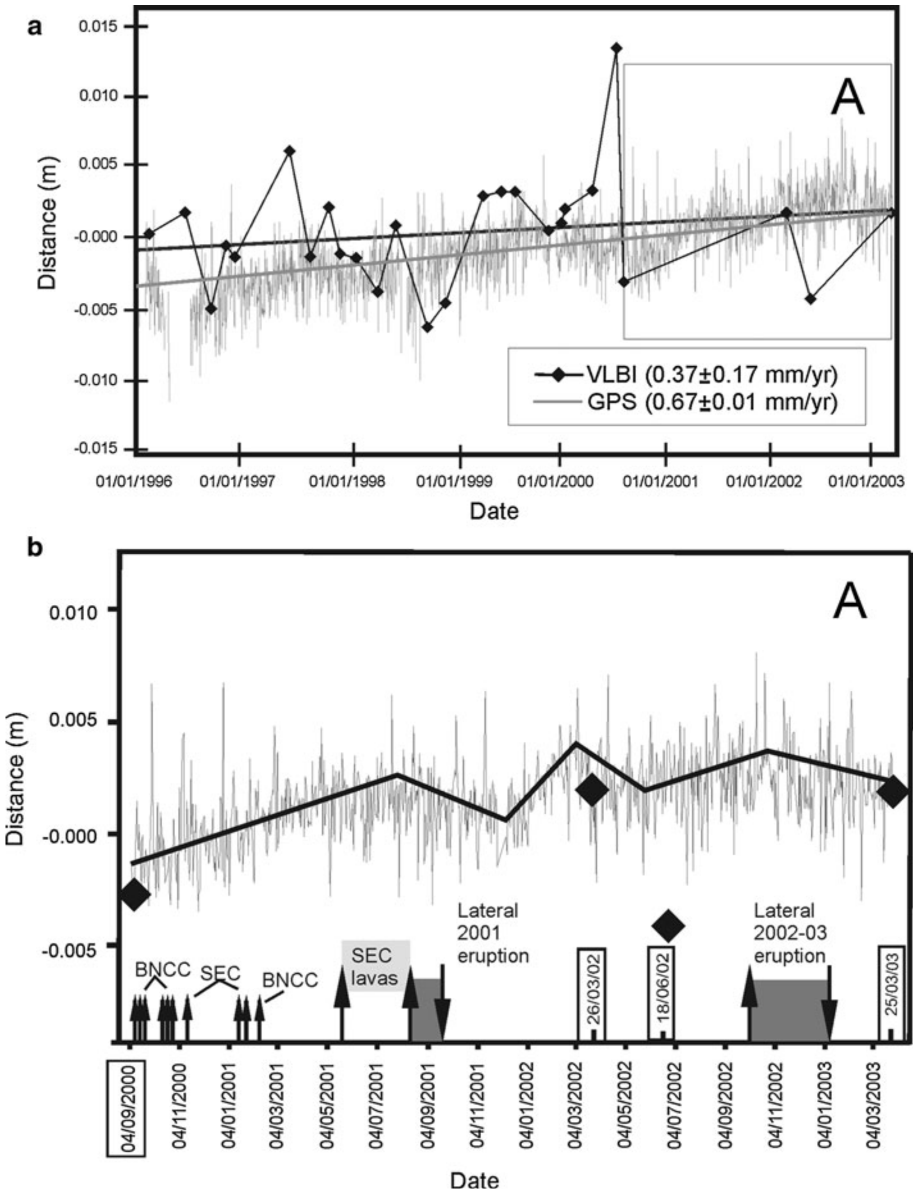

Fig. 4 GPS (*line*) and VLBI (*diamonds*) Noto-Matera baseline length (**a**) and comparison between the baseline length and eruptive (*arrows*) activity (**b**)

submillimetric formal errors, the rms of the times series is 1.6 mm in the relevant period.

The graph in Fig. 3, inset A, shows the trends in the baseline between September 2000 and March 2003. Both the 2001 eruption and the 2002–2003 one are preceded by an increase in the baseline length, and the second one is actually characterized by two successive increases before the eruption. Overall the variations in the Noto-Matera distance observed between 1996 and March 2003 suggest that there is always an increase in the length of the baseline, sometimes in more than one step, before the onset of one or more eruptive events. Moreover, it is interesting to note that the manifestation of the eruptive phenomenon on the surface can precede (2002 eruption), accompany (1996 and 1998 eruptions) or follow (2000 and 2001 eruptions) the decrease in the baseline length.

In our opinion, moreover, the relationships that exist between the soil CO_2 concentrations and the variations in baseline length are very interesting. In fact, the phase in which the baseline was increasing in the period between September 1996 and June 1997 (Fig. 3) preceded some anomalies in CO_2 concentrations measured by Bruno et al. (2001). According to these researchers, between August and September 1997, a rapid and strong increase in soil CO_2 emission occurred in two sites located, respectively, in the SW and E sectors of Etna. This phenomenon indicates an accumulation of CO_2-saturated magma into the deepest (more than 15 km), reservoir beneath the volcano. The decrease in September 1997 in CO_2 concentrations in the two above-mentioned sites suggests a rapid upward migration of a magma batch, which began, according to Bruno et al. (2001), in August 1997. This magma seems to have determined an increase in the eruptive activity observed at the summit craters during October 1997. Between October 1997 and January 1999, various growth and shrinking episodes in the CO_2 concentrations were monitored. According to Bruno et al. (2001), these anomalies are determined by the transferral of magma from deep down towards the surface in steps and linked to the eruptive activity which occurred in the first 10 days of November 1999. La Delfa et al. (2001) came to similar conclusions through the study of geochemical data from the lava erupted from the SEC in a shorter period between September 1998 and February 1999. The VLBI measurements show continuous fluctuations in the baseline length between June 1997 and October 1998 (Fig. 3IIB) confirming Bruno et al. (2001)'s conclusions further in our view.

The longest period, about two and a half months (October 1998–January 1999) in which the CO_2 concentrations remained high is included in a time interval in which there is a marked increase in the baseline length, which is between October 1998 and April 1999 (Fig. 3IIC). This latter phenomenon could be associated with the eruptions at the SEC (lava fountains and Strombolian activity), which developed between the end of 1999 and June 2000.

The temporal trend of the seismicity associated with the fragile deformations shows some interesting correlations with the baseline dynamics. The curve in Fig. 3a (strain release) shows that the highest values for strain release occur immediately before the onset of a lateral eruption (1991–1993 and 2001 eruptions) and also during one (2002 eruption). Earthquake swarms with lower energy affect the volcano sometimes months before eruptions at the summit craters (1995 and 1996 eruptions; Fig. 3a) and also before and during temporal clusters of particularly violent summit eruption phenomena like the eruptions from March 1998 to June 2000 (La Delfa et al. 1999). This seismicity mainly affects a crustal thickness of less than 10 km and shows the highest frequency in the first 6–7 km of crust (La Delfa et al. 2001; Patanè et al. 2006). The highest increases in strain release are found immediately after an increase in the baseline length (June 1997) or during (between October 1998 and April 1999, between September 2000 and July 2001 and between the end of 2001 and October 2002). Instead between December 1999 and August 2000, there is only a modest amount of strain release corresponding to a large increase in the Noto-Matera distance while there is widespread seismicity in the whole volcano area.

Lastly, Bonaccorso and Davis (2004), Puglisi et al. (2004) observed a planar areal dilatation calculated from the line length changes recorded on the Electro-Optical Distance Measurements (EDM) and GPS networks during 1993–2001 periods (Fig. 5). These dilatations were linked to a near continuous expansion of volcano edifice until 2001, determined by the uprise of abundant magma towards the most shallow levels of the crust. Even the tendency line of the VLBI baseline deformation trend shows a general length increase in the 1993–2000 periods (Fig. 6a). Subsequently, a drastic decrease in the baseline length (Fig. 6a) precedes drastic deflation of the volcanic edifice (Fig. 6b) from 2001 to 2003 (Mattia et al. 2007). In this elapsing time, Mt. Etna was affected by two eruptions with strong explosive and effusive activity.

Discussion and conclusions

Comparisons between the trend of Noto-Matera baseline length variations, volcanic activity and seismicity in the Etna area show the complexity of the development over time and space of these phenomenologies determined by a deep cause, which can be traced, in our opinion, to the interaction between the asthenospheric mantle, deep crust and surface crust. The later increases in the baseline, which

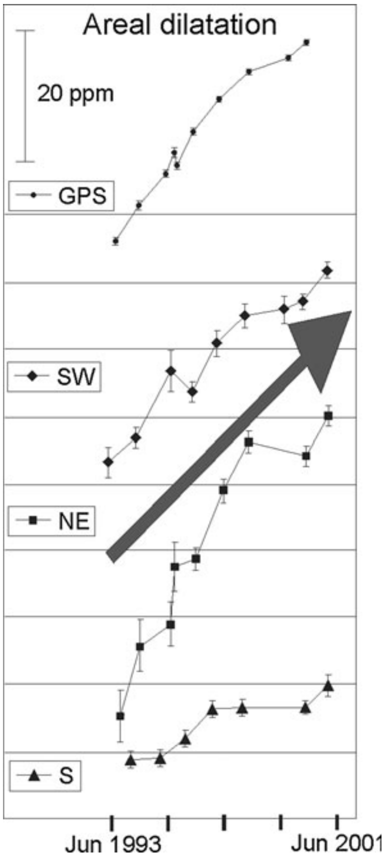

Fig. 5 Planar areal dilatation calculated from the line length changes recorded on the EDM and GPS networks. The areal dilatation represents mean values of the deformation in the following areas: SW is the EDM network in the south-western flank, NE in the north-eastern flank and S in the southern flank. (From Bonaccorso and Davis 2004, modified)

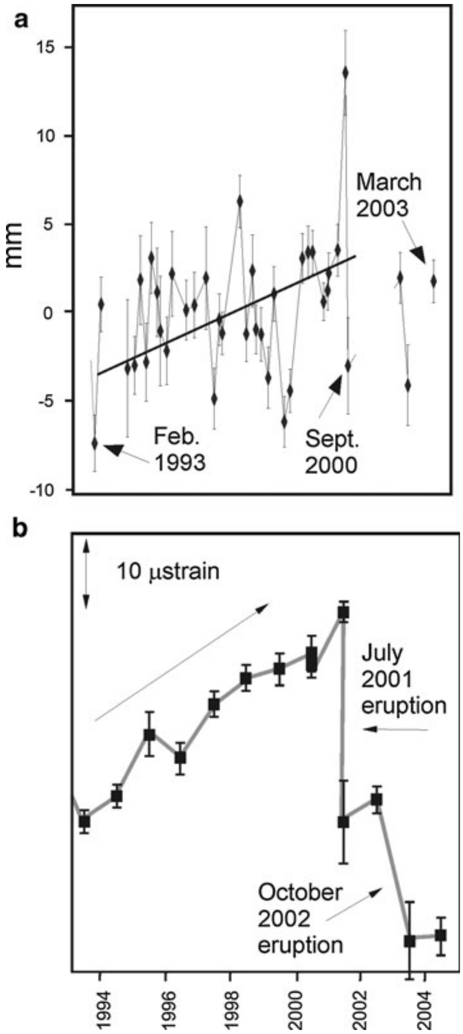

Fig. 6 VLBI Noto-Matera *baseline* (**a**) and SW EDM *baseline* (**b**) (from Mattia et al. 2007) results, which show similar trend in the period 1993–2003

happened five times in a noteworthy measure between September 1996 and October 2002, seem to be unequivocally linked to the genesis or recrudescence of the summit or lateral eruptive phenomena, which occurred in this same period. These followed each other with few interruptions generally of very brief duration. It is therefore possible that the trend in the Noto-Matera distance is determined by a crustal distension, in particular in the deep crust, which is arched upwards by the underlying mantle. This arching assists the divarication of the fractures through which the magma and magmatic fluids flow, which migrate towards the more superficial layers of the crust. The crustal shortening very probably affects the speed with which the magma itself moves from the deepest crust towards the more superficial one. The migration of the molten magma, in fact, is strongly conditioned by its physical–chemical characteristics, by the crust's state of tension and by the state of fracturing which it is crossing. Magma stocking at a shallow crustal depth for shorter or longer periods could moreover be responsible for the delay in migration towards the surface and thus for the onset of an eruptive phenomenon. The beginning of the eruptive phenomena, which occur in the final phase (1996 and 1998 eruptions) or immediately after the crustal shortening (2000 and first semester 2001 eruptions), could have been determined by the compression of the magma encased in the deep crust towards the more superficial layer. Afterwards, the variations in the physical characteristics of the magma (pressure and temperature), which has risen and been stocked in superficial batches, determine the conditions for the onset of the eruptive phenomenon. Indeed, as the temperature and pressure of the surrounding rocks decrease, there can be cases of fractioned crystallization and vesciculation of the gas in the magma, with a substantial increase in the explosivity of the residual molten magma. Phenomena of magma remaining at different crustal levels have been hypothesized for the two lateral eruptions of 2001 and

2002–2003, fed by two types of magma, which produced trakybasalt rich in phenocrysts and more primitive lavas with scarce phenocrysts, chemically very akin to basalts. The two magmas came out contemporarily in both the eruptive episodes, but from different emission points and show chemical–petrographic characters that suggest different ways of migration towards the surface (Clocchiatti et al. 2004). The magma richest in phenocrysts stayed in the crust for longer before being erupted in 2001 and in 2002–2003. These conclusions that derive from petrographical analyses have been further supported by Ferlito et al. (2008) and seem to be confirmed by the trend of the Noto-Matera baseline length variation before the 2002–2003 eruption. In fact, in the period from December 2001 to October 2002, there is a lengthening of the baseline in two successive steps, separated by a 3-month phase of shortening (Fig. 4b). In this case, it is possible to hypothesize a first phase of magma rise and stocking in the most superficial layer of the crust and a second phase of new magma rise, which set off the eruptive phenomenon and probably pushed residual magma stocked in the crust from preceding eruptions without giving eruptive phenomena. Similar considerations can be made for the 2001 eruption; in fact, between September 2000 and July 2001, there is a phase of lengthening of the baseline which would correspond to an uprise of magma from the deep crust towards the surface. This migration culminated in the eruptive phenomenon and assisted the uprise of more differentiated magmas. These stayed in the crust, and before differentiating, they fed other preceding eruptions.

The EDM trend between 1993 and 2003 (Mattia et al. 2007) shows a similar trend to that relative to the Noto-Matera baseline length variation (Fig. 6). Moreover, it shows notable fluctuations (Fig. 6a), which are not found on the areal dilatation graph (Fig. 6b) and which might therefore show a different rheology of the deep crust compared to the superficial one. This latter is colder and more fractured and would seem more suited to keeping the magma in batch from which it migrates towards the surface following variations to the stress field (squeezing effect) or to the increase in explosivity. However, not all the magma is expelled during an eruptive event. Some remains trapped, so that the state of inflation of the superficial crust remains as seems to have been the case in the various eruptive phases between 1997 and 2000 (Figs. 3b, 6b). Furthermore, the mean Noto-Matera strain rate is 7 mm/400 km/8 year = 2, 5 nanostrain/year (Fig. 6a), while the deformation obtained from EDM measurements (Fig. 6b) is 30 microstrain/8 year; so there is a factor 1,000 between the two values. This marked circumstance may be explained considering that the deformation source is closer to EDM networks and more far away from Noto to Matera and the deformation has a strong attenuation, because it travels through a viscous-elastic layer (the crust) extended about 400 km (Noto-Matera baseline). In this context, the seismicity is simply a crustal response to its interaction with the mantle (Patanè et al. 2006), which occurs in different ways according to the degree of penetration of the magma and magmatic fluids into the different crustal levels (La Delfa et al. 2007).

It can therefore be hypothesized that both seismic and eruptive activity could be the induced effect of the mantle's pulsations on the overlying crust, which dilates and contracts. In our opinion, these variations have been well monitored by the VLBI technique, which could constitute a reliable tool to highlight deep crustal movements linked to the activity of the mantle which are at the heart of Etna's geodynamics.

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